

THE LIKELY ORBITAL PERIOD OF THE ULTRACOMPACT LOW-MASS X-RAY BINARY 2S 0918–549

JING ZHONG¹ AND ZHONGXIANG WANG

Shanghai Astronomical Observatory, Chinese Academy of Sciences,
 80 Nandan Road, Shanghai 200030, China

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ABSTRACT

We report the discovery of the likely orbital period of the ultracompact low-mass X-ray binary (LMXB) 2S 0918–549. Using time-resolved optical photometry carried out with the 8-m Gemini South Telescope, we obtained a 2.4-hr long, Sloan r' light curve of 2S 0918–549 and found a periodic, sinusoidal modulation at 17.4 ± 0.1 min with a semi-amplitude of 0.015 ± 0.002 mag, which we identify as the binary period. In addition to 4U 0513–40 in the globular cluster NGC 1851 and the Galactic disk source 4U 1543–624, 2S 0918–549 is the third member of the ultracompact LMXBs that have orbital periods around 18 min. Our result verifies the suggestion of 2S 0918–549 as an ultracompact binary based on its X-ray and optical spectroscopic properties. Given that the donor in 2S 0918–549 has been suggested to be either a C-O or He white dwarf, its likely mass and radius are around 0.024 – $0.029 M_{\odot}$ and 0.03 – $0.032 R_{\odot}$, respectively, for the former case and 0.034 – $0.039 M_{\odot}$ and 0.033 – $0.035 R_{\odot}$ for the latter case. If the optical modulation arises from X-ray heating of the mass donor, its sinusoidal shape suggests that the binary has a low inclination angle, probably around 10° .

Subject headings: binaries: close — stars: individual (2S 0918–549) — stars: low-mass — stars: neutron — X-rays: binaries

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) constitute a large fraction of bright X-ray sources ($L_X \sim 10^{36}$ erg s^{−1}) in the Galaxy. These binary systems consist of an accreting compact star, either a neutron star or black hole, and a Roche lobe-filling, low-mass companion. Thus far approximately ~ 200 LMXBs are known. Among them, there is a class called ultracompact binaries. Different from the majority of LMXBs which contain ordinary, hydrogen-rich mass donors, ultracompact systems are believed to consist of extremely low-mass, either hydrogen-poor or degenerate, companion stars (Nelson, Rappaport, & Joss 1986; Yungelson, Nelemans, & van den Heuvel 2002). As a result, while ordinary LMXBs have a minimum orbital period around 80 min (Paczynski & Sienkiewicz 1981; Rappaport, Joss, & Webbink 1982), ultracompact systems can evolve to extraordinarily small binary separations with orbital periods as short as a few minutes (Podsiadlowski, Rappaport, & Pfahl 2002; Nelson & Rappaport 2003). These ultracompact LMXBs, along with their white dwarf analogues (the AM CVn binaries; see Warner 1995), represent extreme and exotic endpoints in binary and stellar evolution.

While the ultracompact systems had initially been assumed to be relatively rare, the number known has more than doubled to 11 (including 4 globular cluster sources) over the past few years, with a range of orbital periods from 11 to 55 minutes (Ma & Li 2009; Zurek et al. 2009). It is likely that there are more such binaries, because a few candidate systems have been identified either by their peculiar X-ray and/or optical spectral features (Juett, Psaltis, & Chakrabarty 2001; Nelemans et al.

2004; Wang 2004) or through their unusually low optical-to-X-ray flux ratios (Deutsch, Margon, & Anderson 2000; Bassa et al. 2006; in’t Zand, Jonker, & Markwardt 2007). To fully study and understand the ultracompact LMXB population, verification of those candidate systems are warranted. It has shown that the indirect methods for ultracompact binary identification may not be reliable (Shahbaz et al. 2007). In order to verify their ultracompact nature, time-resolved photometry for detecting orbital periodic signals is needed. Moreover once ultra-short orbital periods are found, properties of the binary systems can be further estimated (e.g. Wang & Chakrabarty 2004), helping our understanding of these systems. In an effort to verify the ultracompact nature of the proposed candidates, we have undertaken optical observations aiming to detect orbital flux modulations. We have successfully found the orbital period of the candidate 4U 1543–624 (Wang & Chakrabarty 2004). In this paper we report our discovery of the likely orbital period of another candidate 2S 0918–549.

The LMXB 2S 0918–549 has been a bright X-ray source ($L_X \sim 10^{36}$ erg s^{−1}) and detected by all major X-ray satellites (Juett & Chakrabarty 2003 and references therein). On the basis of comparison of its X-ray spectrum to that of the known ultracompact LMXB 4U 1626–67, the source has been suggested to be an ultracompact binary with a neon-enriched degenerate donor (Juett et al. 2001; Juett & Chakrabarty 2003). Probably because the binary has a low inclination angle (generally $i < 60^{\circ}$; Frank, King, & Raine 2002), no orbital signals were found in X-ray observations of the source (Juett & Chakrabarty 2003). The optical counterpart to 2S 0918–549 was identified by Chevalier & Ilovaisky (1987), $V = 21$, $B - V = 0.3$. Based on its optical-to-X-ray flux ratio, the orbital period of the binary has been suggested to be $\lesssim 60$ min (Juett & Chakrabarty 2003). The source distance is probably 4.1–5.4 kpc, esti-

jzhong@shao.ac.cn, wangzx@shao.ac.cn

¹ Graduate School of Chinese Academy of Sciences, No. 19A, Yuquan Road, Beijing 100049, China

mated from type-I X-ray bursts detected from the source (in't Zand et al. 2005).

2. OBSERVATIONS AND DATA REDUCTION

Time-resolved imaging of 2S 0918–549 was carried out on 2008 December 5 using the 8-m Gemini South Telescope. The instrument was Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004), whose detector array consists of three 2048×4608 EEV CCDs. We used only the middle CCD chip (CCD 02) for imaging. The pixel scale is $0.073''/\text{pixel}$, while the detector was 2×2 binned for our observation. A Sloan r' filter with the central wavelength at 6300 \AA was used. We obtained 179 continuous frames with an exposure time of approximately 24.5 sec. Including 24 sec readout time for each exposure, the total length of the observation was approximately 2.4 hrs. The observing conditions during the early part of our observation (first 59 frames) were relatively poor, with the average seeing [FWHM of the point-spread function (PSF) of the images] being $\simeq 1.0''$ and a few frames having as large as $1.3''$ – $1.5''$ seeing. For the remaining part, the conditions were good with most of the frames having $\lesssim 0.8''$ seeing.

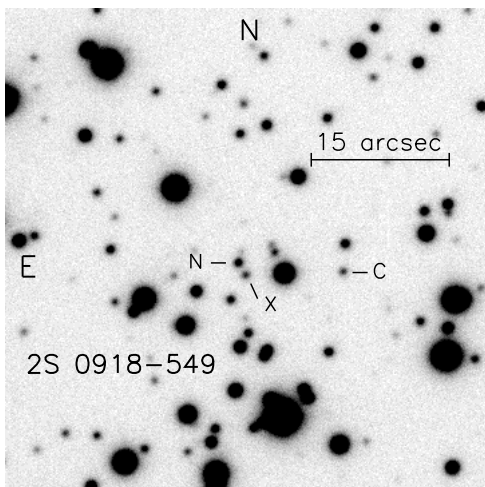


FIG. 1.— Gemini South r' image of the 2S 0918–549 field. Object X is the optical counterpart to 2S 0918–549. The nearby star labeled as N is $1.5''$ away from the target. The star labeled as C was used as a check star.

We used the IRAF packages for data reduction. The images were bias subtracted and flat fielded. The bias and flat frames were from GMOS baseline calibrations taken during the same night.

We performed PSF-fitting photometry to obtain brightnesses of our target and other in-field stars, with a photometry program DOPHOT (Schechter, Mateo, & Saha 1993) used. A finding chart of the target field is shown in Figure 1. As identified by Chevalier & Ilovaisky (1987), there is a nearby star (labeled as N) $1.5''$ away from our target. To avoid possible contamination from this nearby star caused by the poor observing conditions during the early part of our observation, we positionally calibrated the first 59 frames to a reference image that was combined from three high-quality frames. The positions of star N and 2S 0918–549 were determined in the reference image, and were fixed at the positions for photometry of the first 59 frames. At last we excluded

three frames among them from the data. From the three frames, the brightness measurements of star N and other in-field stars obtained were not consistent with the average brightnesses from other frames, and we note that the three frames have the seeing of $1.3''$ – $1.5''$.

Differential photometry was performed to eliminate systematic flux variations in the images. Three isolated, nonvariable bright stars in the field were used. The brightnesses of our targets and other stars in each frame were calculated relative to the total counts of the three stars. A field star labeled as C (see Figure 1) was used as a check star, as it was nonvariable and had similar brightness to our target.

Because we did not request observations of standard stars for flux calibration in our Gemini program and also no standard stars were imaged in the same filter by the Gemini South telescope within at least half a month before and after our observation, we used the BV magnitudes of star N measured by Chevalier & Ilovaisky (1987) to obtain absolute magnitudes of the target and other stars. The transformation formula between r' and BV magnitudes given by Fukugita et al. (1996) was used. We found an average r' magnitude of 20.95 ± 0.16 for 2S 0918–549, where the uncertainty comes from the relatively large uncertainties on the BV magnitudes of star N in Chevalier & Ilovaisky (1987). We note that with the same transformation, $r' = 20.94$ for 2S 0918–549 in Chevalier & Ilovaisky (1987), which indicates that the binary has not had significant changes in its optical brightness. The average r' magnitude of star C was $20.98 \pm 0.16 \pm 0.02$, where 0.02 mag is the standard deviation of star C measured from 176 frames.

3. RESULTS

In Figure 2 the obtained light curves of 2S 0918–549, star N , and the check star C are shown. A periodic modulation in the light curve of 2S 0918–549, while with a low-amplitude, is clearly visible. To determine its period, we applied a phase-dispersion minimization technique (Stellingwerf 1978) with 16 bins of the full phase interval (0, 1) used. The resulting periodogram is shown in Figure 3. The Θ statistic indicates the detection of a periodicity and its two harmonics. Fitting the region near the first minimum with a parabola (Stellingwerf 1978), we found period $P = 17.4 \text{ min}$.

In order to quantify the overall periodic modulation in the light curve, we fit the light curve with a sinusoid. The best-fit has reduced $\chi^2 = 2.3$ for 172 degrees of freedom (DOF), and from the best-fit we found $P = 17.38 \pm 0.13 \text{ min}$ and a semi-amplitude of $0.014 \pm 0.002 \text{ mag}$. The large χ^2 value is mainly caused by large scattering of the first 56 data points due to the poor observing conditions. Excluding them and fitting the remaining data points, we found reduced $\chi^2 = 1.2$ for 117 DOF (P was fixed at 17.4 min). The obtained semi-amplitude was $0.015 \pm 0.002 \text{ mag}$, not having significant changes. Therefore the modulation can be described by a sinusoid with a semi-amplitude of 0.015 mag . The folded light curve at $P = 17.4 \text{ min}$ as well as the best-fit sinusoid are shown in Figure 4. The time at the maximum of the sinusoidal fit (phase zero) was $\text{MJD } 54805.23281 \pm 0.00027 \text{ (TDB)}$ at the solar system barycenter.

4. DISCUSSION

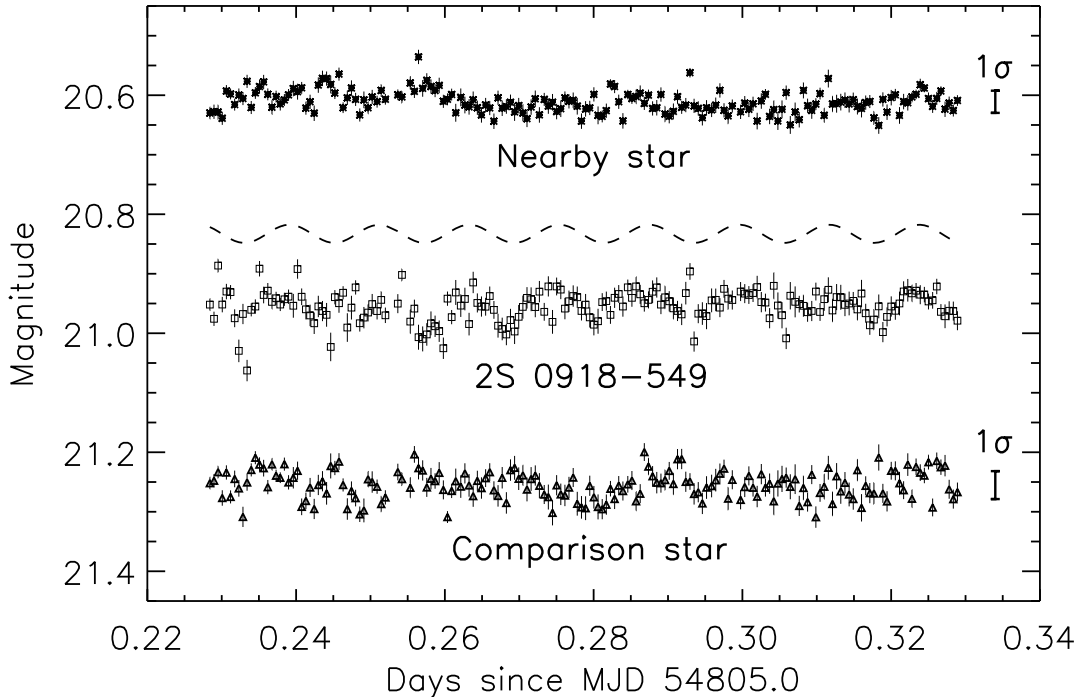


FIG. 2.— r' light curve of 2S 0918–549 (squares). The light curves of the nearby star N (asterisks) and comparison star C (triangles), down-shifted by 0.34 and 0.28 mag respectively, are also shown. A sinusoid (dashed curve) is plotted to help indicate the periodic modulation detected in the light curve of 2S 0918–549.

Using Gemini high time-resolution imaging we obtained an accurate optical light curve of 2S 0918–549 and have discovered a periodic flux modulation in the light curve. A low-amplitude modulation is clearly visible and appears to be coherent. Given the known X-ray and optical properties of 2S 0918–549, it is very likely that we have verified the ultracompact nature of this binary and its orbital period is around 17.4 min (see discussion below). In addition to 4U 0513–40 in the globular cluster NGC 1851 (Zurek et al. 2009) and the Galactic disk source 4U 1543–624 (Wang & Chakrabarty 2004), 2S 0918–549 is the third member of the ultracompact binaries that have orbital periods around 18 min.

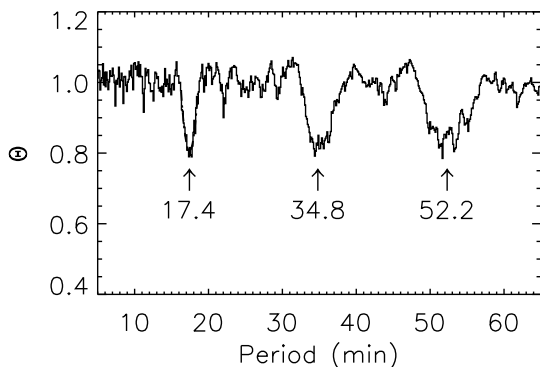


FIG. 3.— Phase-dispersion minimization periodogram. The positions of the minimum Θ statistic at 17.4 min and its two harmonics are indicated by arrows.

We use the discovered orbital period to estimate the mass and radius of the donor. Since the mean density of a Roche lobe-filling companion is determined by

the binary period, our 17 minute period defines a mass-radius relation for the companion, shown as the solid curve in Figure 5. On the basis of the high Ne/O abundance ratio measured through X-ray spectroscopy, the donor in 2S 0918–549 has initially been suggested to be a low-mass C-O white dwarf (Juett et al. 2001; Juett & Chakrabarty 2003). However, the analysis of several type-I X-ray bursts detected from the source possibly indicates that the donor instead is a helium white dwarf (in’t Zand et al. 2005). In any case to compare the donor to stellar models, we use the M-R relations for different types of white dwarfs provided by Deloye & Bildsten (2003). Because extremely low-mass white dwarf donors in ultracompact systems may be thermally bloated compared to cold stars, affecting their M-R relation (Bildsten 2002; Deloye & Bildsten 2003), we show both cold and hot solutions for pure He, C, and O white dwarfs in Figure 5. A helium white dwarf with a mass of $0.034\text{--}0.039 M_{\odot}$ and a radius of $0.033\text{--}0.035 R_{\odot}$, or a C/O white dwarf with a mass of $0.024\text{--}0.029 M_{\odot}$ and a radius of $0.03\text{--}0.032 R_{\odot}$ can fit in the Roche lobe-filling donor.

Modulation of an optical light curve for LMXBs generally arises from the companion star that is heated by the central X-ray source, with the visible area of the heated face varying as a function of orbital phase and the superior conjunction of the companion star corresponding to the observed brightness maximum of the light curve (e.g., van Paradijs & McClintock 1995). It has also been realized that compact LMXBs with extreme mass ratios (such as ultracompact binaries) are potential superhump sources (Haswell et al. 2001). The variation in the light curve of a superhump binary arises

from an elliptical accretion disk, which is developed when the disk extends beyond the 3:1 resonance radius and precesses in the inertial frame due to the tidal force of a secondary star (e.g., Whitehurst & King 1991). Without an independent determination of the binary period (see, e.g., Wang & Chakrabarty 2010), we can not distinguish between the two possibilities for the modulation seen in 2S 0918–549. A superhump modulation may have an asymmetric shape (e.g., Wang & Chakrabarty 2010). However in the current light curve we obtained, no asymmetry is clearly seen. In either case since superhump periods are only a few percent longer than the corresponding orbital periods, the orbital period of 2S 0918–549 is around 17.4 min.

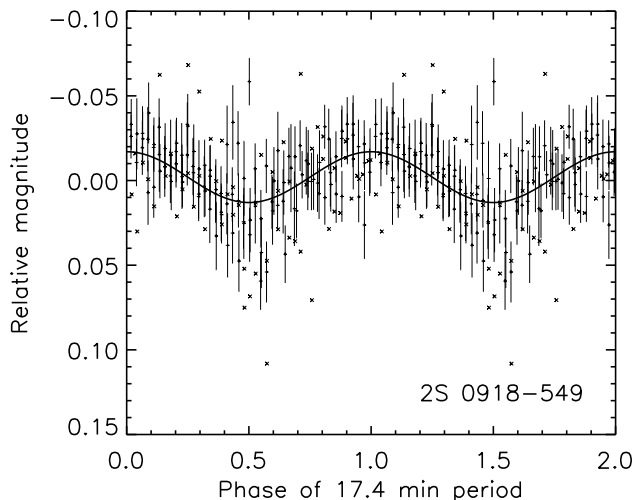


FIG. 4.— r' light curve of 2S 0918–549 folded at 17.4 min. Two cycles are displayed for clarity. The solid curve indicates the best-fit sinusoid with a semi-amplitude of 0.015 ± 0.002 mag. The first 56 data points that were excluded from the fit are shown as crosses.

Considering that the periodic modulation arises from the companion star, the inner face of the companion star in 2S 0918–549 is heated by X-ray emission from the central neutron star and its effective temperature can be estimated. The 0.1–200 keV X-ray luminosity L_X is $1.9 \times 10^{36} d_5^2 \text{ erg s}^{-1}$, where d_5 is the source distance assumed to be 5 kpc and the unabsorbed X-ray flux $F_X = 6.4 \times 10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2}$ given by in’t Zand et al. (2005) is used. The fraction f of the X-ray energy absorbed by the companion is $f = \eta_* (R_2/D_b)^2/4 \simeq 0.004 \eta_* (R_2/0.032 R_\odot)^2 [1 + (q/0.021)]^{-2/3}$, where $\eta_* \sim 0.5$ is the fraction of the received X-ray energy absorbed by the companion, R_2 is the radius of the companion, and D_b is the binary separation distance ($D_b \sim 1.7 \times 10^{10} \text{ cm}$ for orbital period $P_{\text{orb}} = 17.4 \text{ min}$). The mass ratio $q = M_2/M_{\text{ns}}$, where M_{ns} is the neutron star mass and we assume $M_2 = 0.03 M_\odot$ and $M_{\text{ns}} = 1.4 M_\odot$. Following Arons & King (1993), the effective temperature of the companion’s inner face is $T = (f L_X / \pi R_2^2 \sigma)^{1/4} \simeq 46000 d_5^{1/2} \text{ K}$, where σ is the Stefan-Boltzmann constant. The visible area of this hot face varies as a function of the orbital phase, yielding a modulation of $[1 + \sin i \sin(2\pi t/P_{\text{orb}})]$, where i is the inclination angle of the binary (see details in Arons & King 1993). Using such a modulation func-

tion, we can test how the observed modulation is generated. The extinction to the source $A_V \simeq 1.65$, estimated from $A_V = N_H/1.79 \times 10^{21} \text{ cm}^{-2}$ (Predehl & Schmitt 1995) by using hydrogen column density to the source $N_H = 2.95 \times 10^{21} \text{ cm}^{-2}$ (Juett & Chakrabarty 2003). By adding a constant flux component (arising from the accretion disk) to the modulation function and fitting the dereddened light curve of 2S 0918–549 with the modulation function, we find $i \sim 10^\circ$. The estimated low inclination angle is consistent with the non-detection of orbital signals at X-ray energies, which generally indicates $i \lesssim 60^\circ$ (Frank et al. 2002), and likely explains the low-amplitude modulation in the light curve. In order to fully explore properties of the binary by fitting the optical modulation, an advanced binary light curve model is needed (e.g., Deloye et al. 2008; Wang et al. 2011, in preparation).

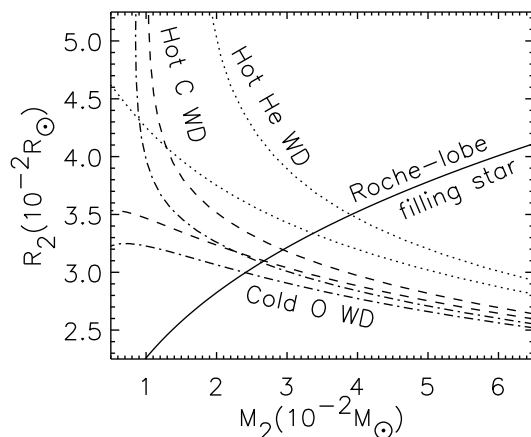


FIG. 5.— Mass and radius values constrained for the companion star in 2S 0918–549. The solid curve is the mass-radius relation for a Roche-lobe-filling donor in a 17.4 min binary. The dotted, dashed, and dash-dot curves represent the model curves for low-mass He, C, and O white dwarfs from Deloye & Bildsten (2003), respectively. For each type of white dwarf, both cold (10^4 K) and hot ($3 \times 10^6 \text{ K}$) core temperature model curves are shown.

As a separate check, we also estimate the distance to 2S 0918–549. Mass transfer in ultracompact binaries is driven by gravitational radiation, and a mass transfer rate in 2S 0918–549 can be estimated to be

$$\dot{M} \simeq 6.2 \times 10^{-10} M_\odot \text{ yr}^{-1} \left(\frac{M_{\text{ns}}}{1.4 M_\odot} \right)^{2/3} \left(\frac{M_2}{0.03 M_\odot} \right)^2 \times \left(\frac{P_{\text{orb}}}{17.4 \text{ min}} \right)^{-8/3}.$$

Since $L_X = GM_{\text{ns}} \dot{M} / R_* = 4\pi d^2 F_X$, the unabsorbed 0.1–200 keV X-ray flux of 2S 0918–549 would imply $d \sim 9 \text{ kpc}$, where conservative mass transfer onto a $1.4 M_\odot$ neutron star is assumed and $R_* \simeq 10 \text{ km}$ is the neutron star radius. The distance value is larger than the 4.1–5.4 kpc range derived from type-I X-ray bursts. We note that \dot{M} is sensitive to M_2 . For example, if $M_2 = 0.024 M_\odot$, where an oxygen white dwarf has to be assumed, the distance could be lowered to 7 kpc. A larger X-ray flux can also help lowered the distance. As recorded in an *ASCA* X-ray observation in 1995,

approximately 7 times larger X-ray flux was detected (Juett & Chakrabarty 2003; in't Zand et al. 2005). If that *ASCA* flux is considered, the distance would be lowered to ~ 4 kpc. However, given the known X-ray flux history of 2S 0918–549, its 2–10 keV flux has been stable and around 10^{-10} erg s $^{-1}$ cm $^{-2}$ (in't Zand et al. 2005), suggesting that the *ASCA* flux was only a one-time event.

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Facility: Gemini:South (GMOS)

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